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SOME RESULTS OF VELOCITY FLUCTUATION MEASUREMENTS IN THE INITIAL SECTION OF AN AXISYMMETRIC JET

by

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by

A. I. Schidlovsky

Summary

A turbulent axisymmetric jet was investigated to determine the axial, radial and tangential components of the fluctuating velocity as well as the axial and radial components of the velocity correlation coefficients at a given point. Also determined were the symmetric and asymmetric correlation coefficients and the transverse turbulence scale. The jet was 150, 440 and 2200 mm in diameter; measurements were taken in the initial section (submerged jet) where the boundary layer is two-dimensional. The results of measurements are shown graphically as families of curves describing the mean velocity, the turbulence intensity, the fluctuating velocity component and various cross plots of these parameters.

SOME RESULTS OF VELOCITY FLUCTUATION MEASUREMENTS IN THE INITIAL SECTION OF AN AXISYMMETRIC JET*

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Known studies of the microstructure of the boundary layer in the initial section of axisymmetric submerged turbulent jets have been carried out, as a rule, in test stands with small nozzle diameters [1-7]. Since the length of the initial section determined from mean velocities is known to extend over several jet diameters, the measurement range in these studies had relatively small lateral and axial dimensions.

The purpose of the present study was to find the distribution of the axial, radial and tangential components of the fluctuating velocity, of the correlation coefficient of the axial and radial components of the fluctuating velocity at a given point, of the symmetrical and asymmetric correlation coefficients, and of the integral transverse turbulence scale in the initial section of turbulent jets of sufficiently large diameter (D = 150, 440 and 2200 mm). Experiments were carried out on the first two jet diameters, where the boundary layer can be considered plane since the transverse curvature of the flow does not exert any effect in this case.

All measurements of mean and fluctuating velocities were carried out with hot-wire anemometers; constant-temperature hot-wire anemometers built by the "Disa Elektronik" firm were used for the bulk of the measurements. The mean velocity and the axial component of the fluctuating velocity were measured with a single-wire probe having a wire diameter of 8μ and a length of 1.3 mm. A cross-shaped two-wire probe (length of each wire 2.5 mm) two

* Translated from Prom. Aerodinamika [Industrial Aerodynamics], No. 27, pp. 111-120 (1966).

hot-wire anemometers and a correlator built by the same firm were used to measure both the axial and radial components of the fluctuating velocity as well as the correlation coefficients. Fluctuations of the transverse velocity were measured with an ETAM-3A hot-wire anemometer and an angular hot-wire probe in the initial section of the 2200-mm diameter jet at a station $x = 1600$ mm, where the boundary layer was approximately 350 mm thick. (Note: these measurements were carried out by the author together with V. M. Filippov). At all other stations measurements were carried out with the hot-wire anemometer of the "Disa Elektronik" firm.

Control tests showed that the flow in jets is rigorously axisymmetric, and therefore measurements were carried out along one radius of the jet in a velocity range of 12-42 m/sec.

As studies of velocity fluctuations in the boundary layer on the nozzle wall near its exit section have shown, this layer was turbulent in all cases. Consequently, the entire mixing zone formed behind the nozzle was turbulent, i.e., there was no inlet laminar region.

Measurement Results

The distribution of the mean velocity and turbulence intensity $\epsilon_u = \sqrt{\overline{u'^2}}/u$ within the limits of the boundary layer and the core of the 440-mm diameter jet is shown in Fig. 1. Here, u and u' are the mean and fluctuating velocity, respectively.

In Fig. 2, similar results are shown for the quantity $\sqrt{\overline{u'^2}}/u_o$, where u_o is the exhaust velocity of the jet.

In Figs. 3 and 4 the results shown in Figs. 1 and 2 are represented as a function of the dimensionless ratio y/x, where y is measured from the

longitudinal axis which is an extension of the nozzle edge. Results of measurements with the cross-shaped two-wire probe $\left(\sqrt{\overline{u'^2}}/u_o \text{ and} \sqrt{\overline{v'^2}}/u_o\right)$ are shown in Fig. 5. A comparison of the data given in Figs. 4 and 5 shows a slight discrepancy (17% and 15.5%) between the maximum values of $\sqrt{\overline{u'^2}}/u_o$ measured with the one-wire and two-wire probes. It is interesting to note that, according to data in reference [6], the maximum value of the quantity $\sqrt{\overline{u'^2}}/u_o$ is equal to 16%.

Results of similar measurements on the 2200-mm diameter jet are shown in Fig. 6, which, in addition to the mean velocity profile, also gives the fluctuation intensities of all three velocity components as a function of y/x. The same results are shown in Fig. 7 when the rms value of the fluctuating velocities is referred to the velocity u_o.

The above data (see Figs. 1 and 2) show how turbulent perturbations arise in the boundary layer of a jet and how fluctuations penetrate into the constant-velocity core. At the same time, a region can be identified in the core of the jet within which the turbulence intensity is practically constant and is equal to the initial turbulence intensity at the nozzle exit. This region can be approximately represented in the form of a cone with a height of the order of one jet diameter (see dotted line in Fig. 2).

The relations given in Figs. 3-7 illustrate the well-known fact that fluctuating velocity profiles are universal in the mixing section of two streams [1-7]. It should be noted that the scatter of experimental points increases as one approaches the outer limit of the boundary layer; in this region, it is difficult to measure both the mean and fluctuating velocities in view of the intermittent nature of the flow and the very small values of

the mean velocity.

Measurements of the radial component of the fluctuating velocity, performed in the 440-mm diameter jet, and of the radial and tangential components in the 2200 mm jet have shown that the axial component of the fluctuating velocity is greater than the other two components, which are practically equal (Figs. 5-7).

The fact that the axial component is greater than the radial component was also noted in the studies of Liepmann and Laufer [5] and also in the work of Van der Hegge Zijnen [8]. However, the third component was not measured in the above studies.

In Fig. 7, showing experimental results for a 2200-mm diameter jet, a mean curve is plotted, which corresponds to experimental points for a 440-mm and 25.4 mm jet [6].

The measurements performed have shown that the width of the boundary layer, determined from points in which the velocity amounts to $u/u_o = 0.10$ and 0.90, is equal to $\delta = 0.18x$. It is interesting to note that, according to Reichardt's experiments [9], the width of the mixing zone, determined from points in which $(u/u_o)^2 = 0.10$ and 0.90, is $\delta = 0.098x$, whereas this width is $\delta = 0.11x$ according to the data given in Fig. 6.

The mean velocity at $y/x = 0$ is equal to $u/u_o = 0.63$. Results of measurements of the correlation coefficient, R_{uv}, of the axial and radial velocity components, performed in a 440-mm diameter jet, are shown in Figs. 8 and 9.

The factor R_{uv} decreases monotonically from the inner edge of the boundary layer ($y/x < 0$, $R_{uv} \approx 0.3$) towards the outer edge ($y/x > 0$, $R_{uv} \approx 0.1$).

These measurements were performed at stations x = 440 and 550 mm, where the thickness of the boundary layer was δ = 99 and 110 mm, respectively. The relation for Reynolds' shear stresses $\overline{u'v'}/u_o^2 = R_{uv}\sqrt{\overline{u'^2}}/u_o \cdot \sqrt{\overline{v'^2}}/u_o$ is shown in Fig. 10 and the distribution of the ratio τ/τ_{max} is shown in Fig. 11.

The above values of the normal and tangential Reynolds' stresses can be used together with the mean velocity profile for calculating the distribution of the mixing length across the boundary layer of the jet with the aid of the relations

$$\sqrt{\overline{u'^2}} = \ell_u \frac{\partial u}{\partial y} \ , \sqrt{\overline{v'^2}} = \ell_v \frac{\partial u}{\partial y} \ , \quad \overline{u'v'} = \ell_o^2 \left(\frac{\partial u}{\partial y}\right)^2 \ .$$

Results of the calculation by means of these formulas of the three dimensionless lengths ℓ_u/x, ℓ_v/x and ℓ_o/x as a function of y/x are given in Fig. 12. An examination of these data shows that only the mixing length, ℓ_u, remains practically constant across the boundary layer of the jet. The values of ℓ_o and ℓ_v decrease monotonically towards the outer edge of the jet.

Apparently, the accuracy of calculation can be noticeably increased by taking this fact into consideration when using Prandtl's formula for shear stresses. An analogous conclusion has been made previously in [5], namely that mixing length across the jet is no longer constant.

As was noted before, the distributions of the radial and tangential components of the fluctuating velocity in a ⌀200-mm diameter jet practically coincide (see Figs. 6 and 7). This fact has made it possible to calculate for a 440-mm diameter jet the value of the square of the mean turbulence intensity, which is proportional to the kinetic energy of turbulence

$\overline{u'^2_m} = \frac{1}{3}\left(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}\right)$. Fig. 10 shows the distribution of the ratio $\overline{q^2} = \overline{u'^2_m}/u_o^2$ and also of the quantity $a = \overline{u'v'}/\overline{u'^2_m}$.

The flow in the boundary layer of the jet is axisymmetric. Therefore it is interesting to examine to what extent the ratio $\overline{u'v'}/\overline{u'^2_m}$ is no longer constant; according to Townsend, this must occur in symmetric flows. As can be seen in Fig. 10, this ratio is practically constant only in the inner region of the boundary layer when y/x = 0 to -0.07.

In order to calculate the transverse integral scale $L_{uu} = \int_{-\infty}^{\infty} R_{uu} d\eta$ the distribution of the symmetric correlation coefficient of the fluctuations of the axial velocity component

$$R_{uu} = \frac{\overline{u'(y+\eta)u'(y-\eta)}}{\sqrt{\overline{u'^2}(y+\eta)}\sqrt{\overline{u'^2}(y-\eta)}}$$

was measured across the jet at several stations along jets of 440 mm and 150 mm diameter.

This scale was found to be approximately constant in the central region of the boundary layer (Fig. 13) and equal to $L_{uu} = 0.03x$ (Fig. 14). The symmetric and also the asymmetric correlation coefficients

$$R_{uu} = \frac{\overline{u'(y)u'(y+\eta)}}{\sqrt{\overline{u'^2}(y)}\sqrt{\overline{u'^2}(y+\eta)}},$$

obtained when the mobile heat probe was moved away from the stationary probe, were measured at stations close to the nozzle in the boundary layer of a 150-mm diameter jet; these measurements disclosed rather large negative

correlations. As an example, Fig. 15 shows the results of measurements of the correlation coefficient R_{uu} when the distance between the probes is increased symmetrically. The region of negative values of R_{uu} becomes smaller with increasing distance from the nozzle and only positive values of R_{uu} are observed at a distance of approximately $x \gg 60$ mm. This phenomenon is apparently due to the presence of a certain periodic process occurring in the flow in the immediate vicinity of the nozzle edge.

E. M. Minskii [10] has made the assumption and has proven experimentally that there is a connection between the turbulence scale and the mixing length in an open channel flow. A comparison of the values, obtained in the above study, of the mixing length $\ell_u/x \simeq 0.03$ and of the integral transverse turbulence scale $L_{uu}/x \simeq 0.03$ also indicates that there is a definite connection between these characteristic geometric dimensions in the mixing layer of the jet.

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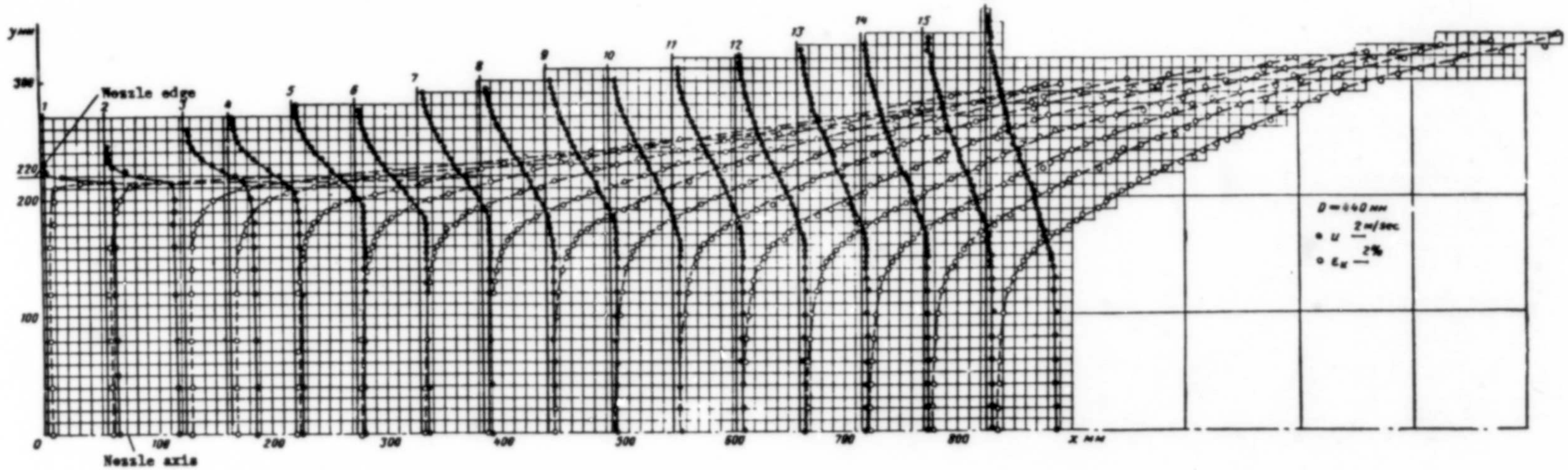
y mm
x mm
Nozzle edge
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0
100
200
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1
2
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12
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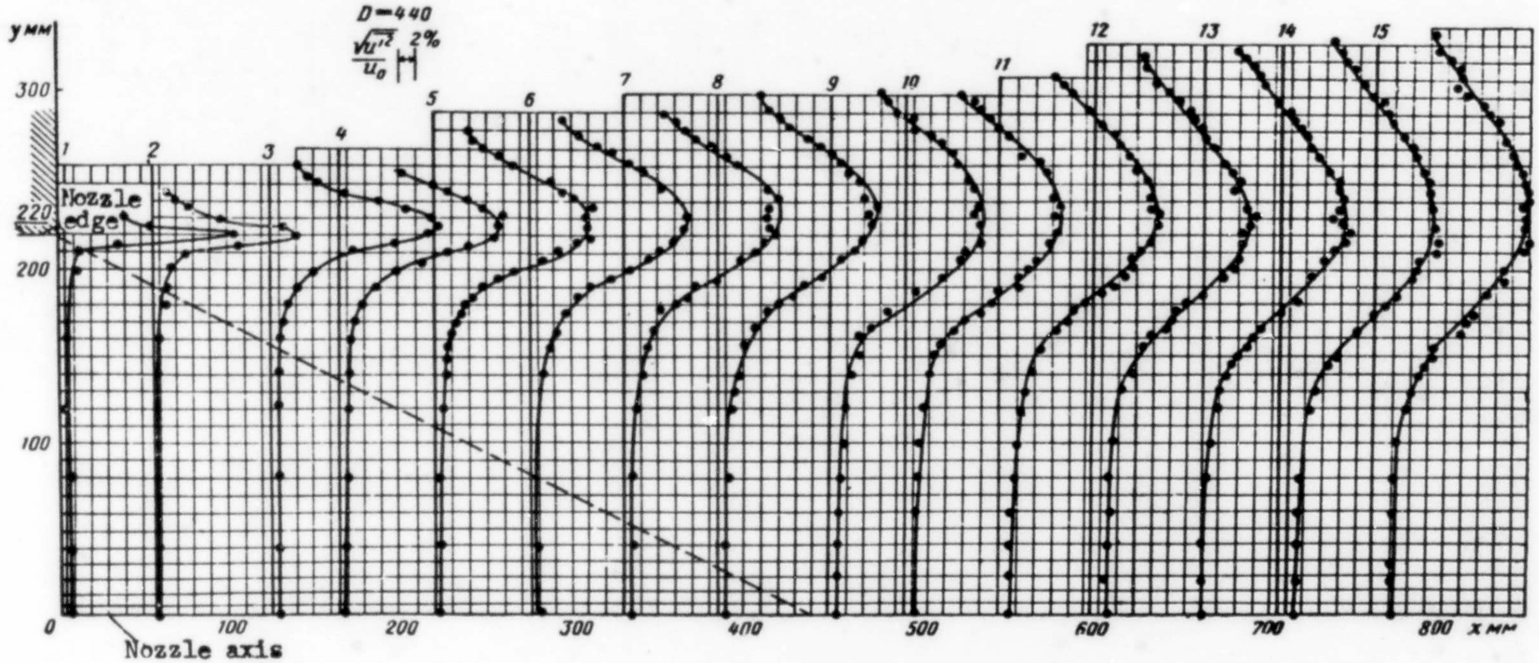
16
D = 440 mm
u 2 m/sec
ε 2%

Figure 1.



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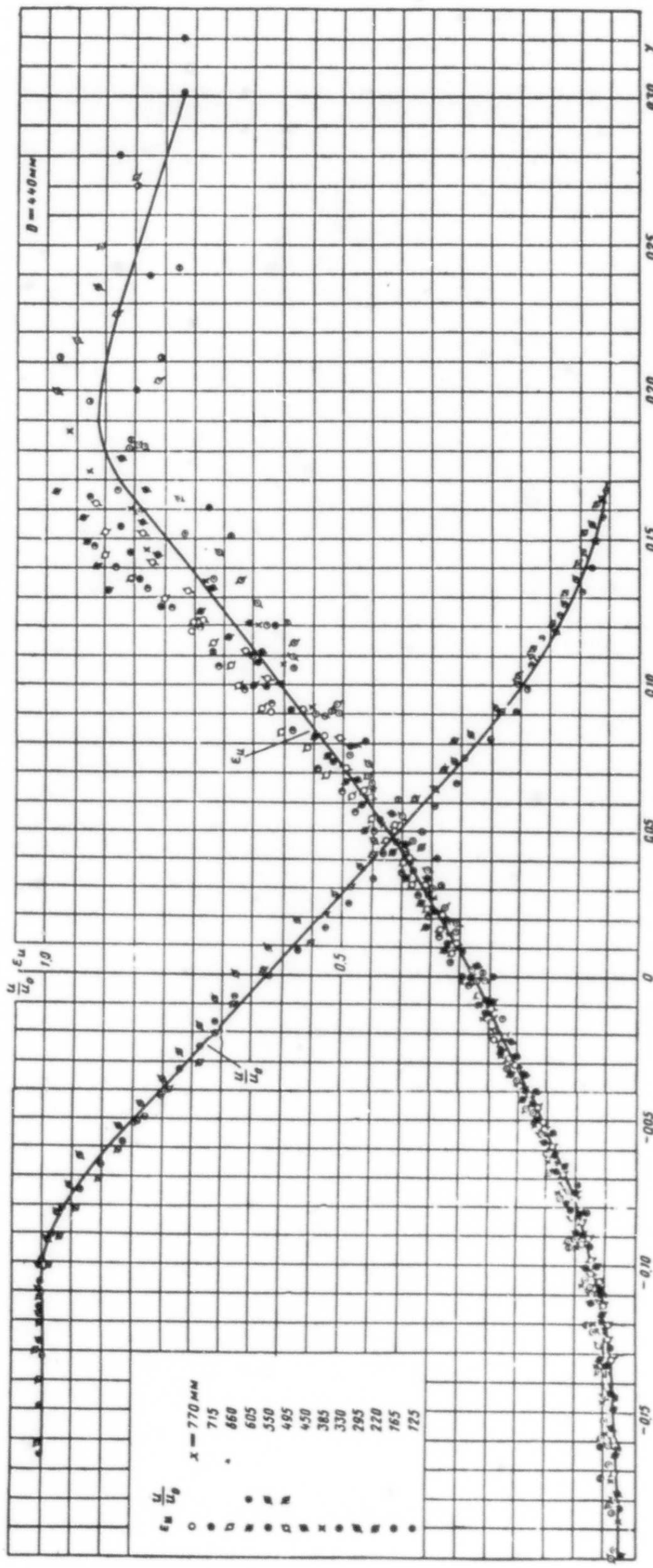
D = 440 мм
$\frac{u}{u_0}$, ε_u
1.0
0.5
ε_u
$\frac{u}{u_0}$
-0.15
-0.10
-0.05
0
0.05
0.10
0.15
0.20
0.25
0.30
$\frac{y}{x}$
x — 770 мм
715
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605
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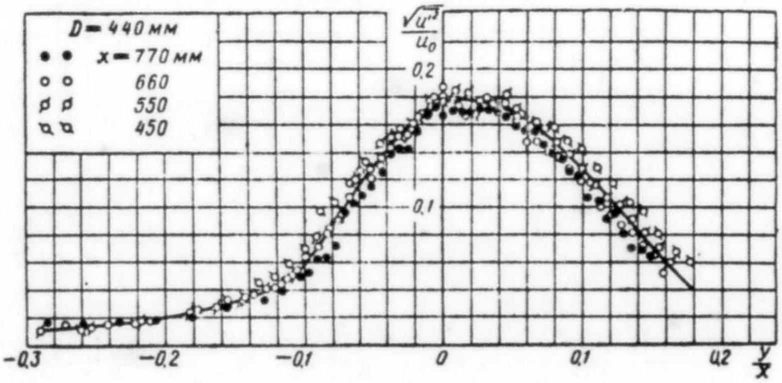
495
450
385
330
295
220
165
125

Figure 3.



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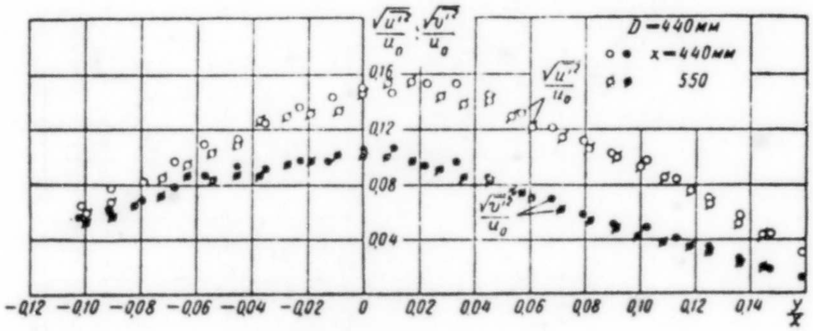

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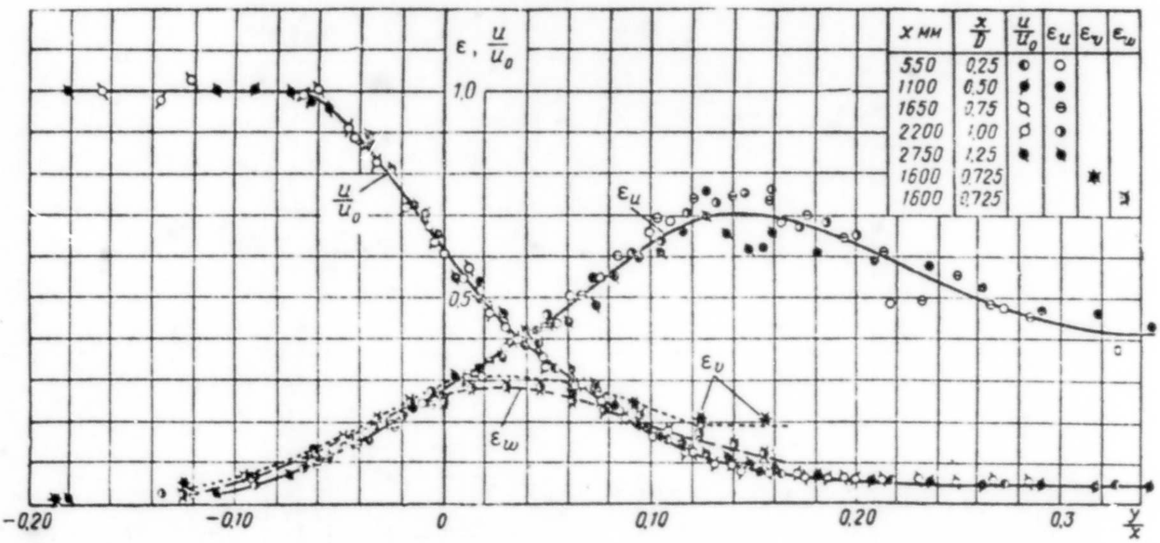

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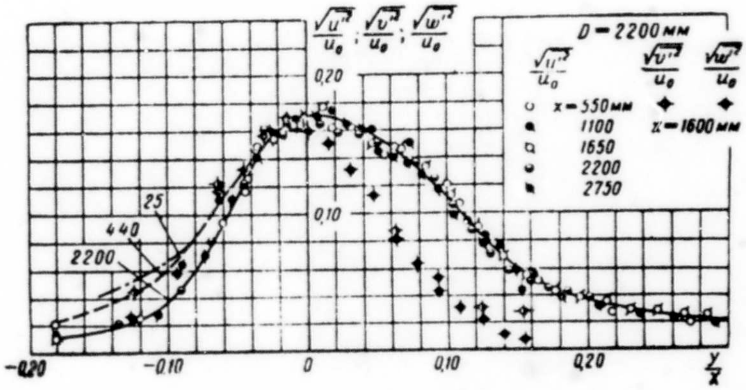

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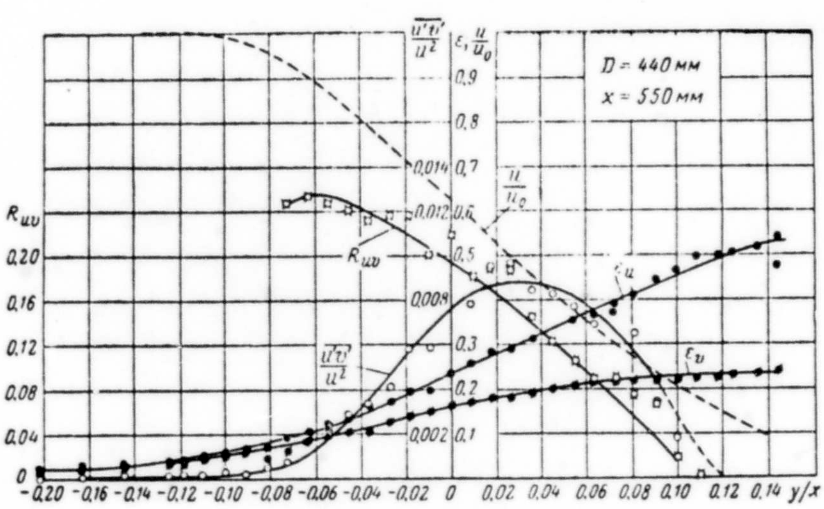

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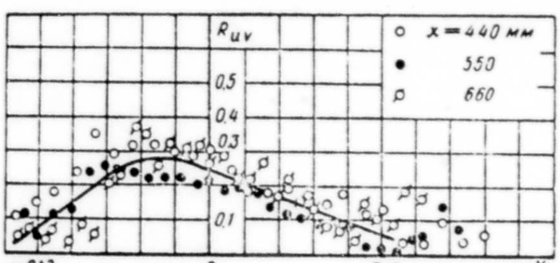

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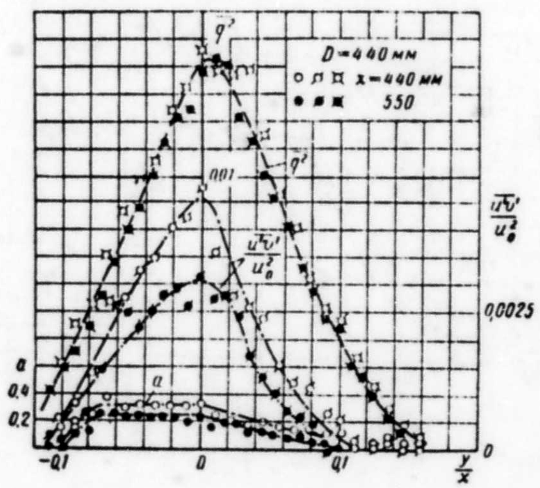

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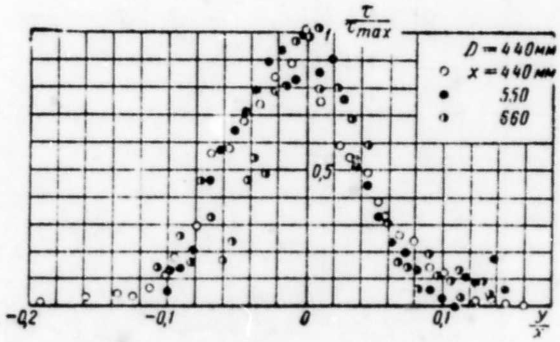

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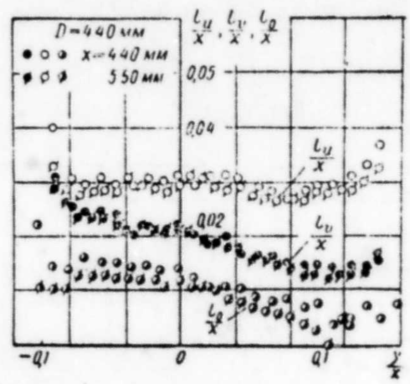

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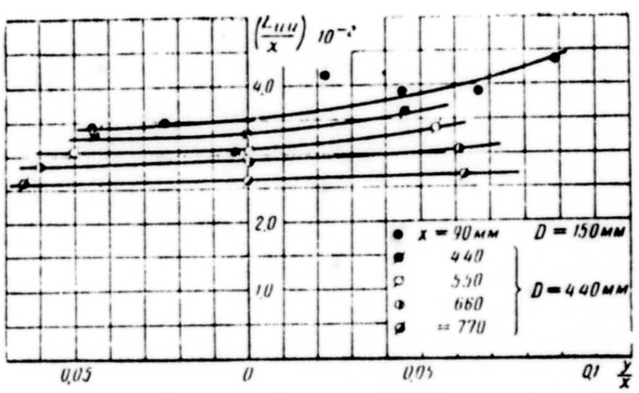

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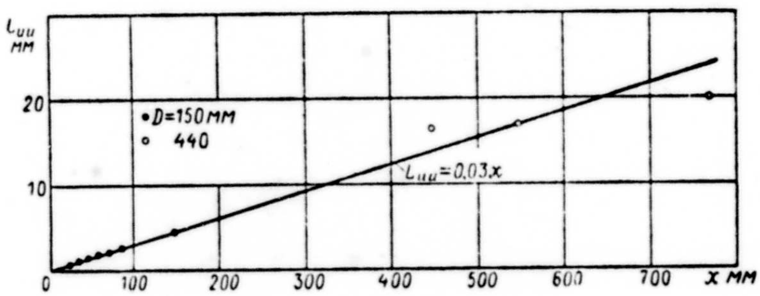

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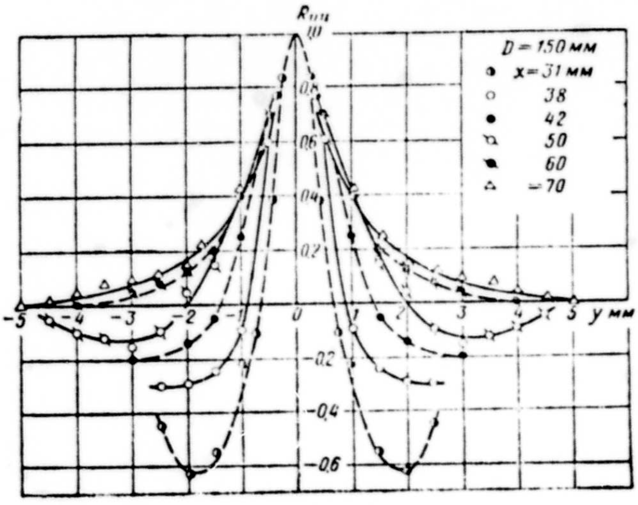

Figure 15.

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13. ABSTRACT

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